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CONSTITUTIVE FEATURES OF SOLIDS AT SHOCK-WAVE LOADING RATES

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ABSTRACT. Solids subjected to high-velocity impact or explosive loading exhibit unusual transient and post-shock properties during the extremely brief period associated with the shock-wave risetime and release. These features can include a unique solid-state shock viscosity behavior, anomalous transient shock-hardening effects, heterogeneous shear effects during the shock risetime, and shock-induced solid state and metallurgical transformations. Improved methods in time-resolved instrumentation have been critical in the emerging understanding of these constitutive features. An increasing sophistication in physical and computational modeling is required to incorporate these effects in applied problems of dynamic solid mechanics.

I. SHOCK-WAVE CONCEPTS. An explosion, radiation deposition, or high-velocity impact can lead to a brief but intense pressure loading of a solid body through the propagation of a compression shock wave. Pressures achieved by conventional methods range from a few to several hundred GPa. Fundamental properties of shock waves are most readily appreciated through consideration of a normal one-dimensional shock such as might be produced by the planar impact of flat plates [1-3]. The shock transition in a single phase material occurs through the passage of a pressure wave with a risetime so brief that it is usually regarded as a discontinuity. The shock state is characterized by changes in the pressure, P, material velocity, u_p, specific volume, V, and specific internal energy, E. The kinematics of the wave are determined by a unique shock velocity, U_s. Fundamental laws governing conservation of mass, momentum, and energy lead to the Hugoniot conditions relating variables through the shock transition,

$$V/V_o = (U_s - u_p)/U_s, \tag{1}$$

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$$P - P_o = U_s u_p / V_o, \tag{2}$$

$$E - E_o = \frac{1}{2}(P + P_o)(V - V_o). \tag{3}$$

A thermodynamic description of the shock transition for a particular material is completed with a representation for the Hugoniot, which is an experimentally determined pressure-volume relation for the locus of shock pressure-shock volume states achieved through a sequence of increasing amplitude shock waves.

Under sufficiently high shock pressures in a solid, material response has usually been regarded as fluid in the sense that deviatoric stress and strain values are neglected in relation to hydrodynamic values [1-3]. In shock loading to pressures of about 20 GPa or lower in metals and perhaps twice that in refractory materials, this assumption is becoming recognized as a poor approximation in that effects of material strength can profoundly influence physical processes [4-6]. In addition, the fact that a shock wave has a brief but finite risetime cannot always be ignored in consideration of the mechanisms for the shock-induced processes [7,8].

II. MICROSTRUCTURAL FEATURES IN THE SHOCK TRANSITION. Microstructural features in the deforming solid are becoming increasingly recognized as important to the stress wave and flow process. Constitutive modeling efforts are tending toward better understanding and explicit treatment of the material microstructure in addressing elastic responses, strength, the yield process, flow and phase transformation. Two microstructural aspects appear important. First is the pre-existing microstructure including grain structure, porosity, and internal stress fields. The second is a transient deformation microstructure induced during the shock process. The former microstructure dominates wave propagation for stress amplitudes near the strength limit of the material but becomes of decreasing importance for shocks significantly stronger than the material strength. In contrast, an induced deformation microstructure achieves increasing importance in the extreme high-rate flow associated with a strong shock wave. These microstructural effects appear to play a significant role in both stress-wave propagation and the material processes occurring under stress-wave loading.

The pre-existing microstructure of a solid governs the details of nonlinear stress waves which load the material beyond the level of plastic yield or fracture. Microstructural features profoundly influence elastic wave propagation through frequency dependence and dispersion. In large amplitude wave propagation such elastic response leads to dispersed or ramped waves and governs the loading rate at which yield or other critical stress levels are achieved. Grain structure, through size and anisotropy, affects onset of plastic flow or brittle failure. Grain size influences the yield stress level and, under impact loading rates, can lead to rate-dependent yield phenomena. Grain anisotropy can cause broadening of the yield process and leads to recoverable elastic response in multiple-wave shock loading experiments [9]. Porosity is accompanied by strong local stress fluctuations, providing sites for premature yielding, fracture and phase transformation. Large local deformation leads to transient local hot spots which can accelerate thermally-activated rate processes under shock loading. Collapse of pore volume at shock deformation rates involves microinertial effects, which can lead to rate-dependent response of the bulk material [10,11]. Dynamic fracture or spall is governed by the nucleation rate and growth of microstructural defects and flaws inherent in the material. Under impulse loading, time-dependent damage growth and rate-dependent spall strengths are observed [12,13]. Tensile fracture damage can occur through growth and coalescence of a population of microcracks in brittle solids or through void nucleation at atomic or microstructural defects followed by catastrophic cavitation in ductile solids [14,15]. The intensity of damage in terms of the density of microcracks or voids per unit volume appears to be controlled by the loading rate through a balance of the rates of nucleation and growth, and microstructural energy effects [16].

III. HETEROGENEOUS SHEAR. As the amplitude of the shock wave becomes increasingly larger than the strength of the material, existing microstructure properties become less important. Complex wave structure due to yielding or phase transformation tends to become overdriven and the shock wave degenerates toward an extremely rapid rising pressure pulse, perhaps a few nanoseconds in duration and a few tens of micrometers in extent. The width of the wave is governed by an effective viscous response of all of the dissipative processes occurring within the shock. Although gross microstructure such as porosity continues to influence the shock process through void volume crushup and intense shock heating, more subtle microstructure, such as grain size and orientation, and existing dislocation structure, defects, or impurities, seems to be of lesser importance.

Modeling the shock pressure as a brief, intense, homogeneous deformation from the initial to the shock state with the attendant homogeneous temperature and entropy rise appears to be too simplistic, however. This approach is incapable of explaining a rich body of shock-wave phenomena, including electric and magnetic effects, partial melting and thermally-activated solid state transformations, shock-induced chemical changes, and a host of metallurgical effects. A large body of post-shock metallurgical investigation exists in the literature (see, for instance, Mikkola [17], Murr [18], Grady *et al.* [8]). Although fraught with interpretational difficulties due to uncertainties in the shock unloading path and post-shock metallurgical changes, metallographic optical and transmission electron microscope studies seem to indicate that the shock deformation is an extremely heterogenous and turbulent process. A highly heterogeneous deformation process is further strengthened by recent advances in methods for measuring time-resolved stress waves in solids which reveal features in the shock deformation wave structure that are not easily reconciled with present theories of homogeneous shock deformation and high rate flow [19,20].

Recent theoretical efforts which attempt to account for the heterogeneous deformation process during shock loading reveal that significantly higher than average temperatures may persist briefly in deformation zones within the shock wave [7,21,22], and calculations indicate local temperature rises of a few hundred to a few thousand degrees Kelvin, depending on the magnitude of dissipation, the thermal conductivity, and the mass fraction of intensely deformed material. Such temperatures are sufficient to complete phase transformation by thermal activation within the shock risetime and localized melting within the shock can occur [23]. Dimensions of shear zones and temperature gradients expected to occur after passage of the shock wave suggest extremely rapid cooling rates (on the order of 10^{11} K/s), capable of quenching transformed material and submicrostructure within the high-pressure shear-banded material.

IV. SHOCK-WAVE VISCOSITY. An important aspect of the microstructure and material property changes which occur during passage of a shock wave is the time duration within which they must occur. Improved methods for measuring time-resolved profiles show that shock compression is not discontinuous but occurs within one to a few hundred ns over the stress range of about 1 to 10 GPa with the risetime decreasing rapidly with increasing stress amplitude. Irreversible deformation processes occur within the plastic portion of the wave. The plastic wave can change with time during the early evolution of the profile but achieves a steady shape after a short propagation distance due to a balance between the nonlinearity of the material compression behavior and rate-dependent dissipative processes which tend to disperse the wave.

In the hydrodynamic approximation of shock compression, a viscous relation has been found useful in characterizing material behavior. In more general elastic-plastic response, a more complicated viscous behavior is expected. It has been useful, however, to classify the dissipation over a steady-wave shock compression process by an effective viscosity. The viscosity coefficient is quantified experimentally as the ratio of the maximum viscous stress, which is proportional to the maximum difference between the Rayleigh line and the Hugoniot, and the strain rate from the maximum slope of the wave profile.

Recently, steady-wave profile data on a number of metals and nonmetals have been examined for risetime behavior [24]. A plot of steady-wave stress jump against strain rate for materials which include copper, aluminum, beryllium, iron, quartz, and magnesium oxide indicate unexpected consistencies. Strain rate increases as the fourth power of the stress jump for all material examined. This implies that the shock viscosity decreases as the square root of strain rate exhibiting a non-Newtonian behavior.

Swegle [24] has incorporated a square root viscous relation within a general Maxwell-like plasticity model and has readily reproduced the work hardening and steady-wave response observed experimentally. These calculations were performed without including artificial viscosity.

Factors governing shock viscosity and risetime of the plastic wave have not yet been determined. Viscous flow should be associated with the microscopic process of dislocation multiplication and motion, vacancy production, precipitate alteration, *etc.* There are tentative indications, however, that shock wave risetimes and viscosity are governed by more fundamental, mechanism independent, energy principles. If so, the microscopic shock process would be an effect rather than a cause, occurring in the most energetically favorable way, consistent with the time constraints. This idea is speculative, but it is clear that a better understanding is necessary here before a comprehensive theory of the shock deformation process will emerge.

V. ANOMALOUS SHOCK HARDENING. Recent measurements of plastic wave profiles in metals such as aluminum [4], copper [25], and beryllium [26], indicate strength properties at the Hugoniot state and viscous effects within the shock front which are unique in behavior and not readily explained [4,8,25,26]. Attempts to rationalize metallographic studies of shocked samples, which indicate strong heterogeneities in the microscale deformation with the very high rate of flow determined from the measured wave profiles, indicate that adiabatic shear deformation and thermal trapping may play an important role here also.

A unique shock wave experiment in which a second unloading or reshock wave is passed through the metal within microseconds after the initial deformation shock wave reveals further elastic-plastic response with significantly enhanced material strength. It is difficult to explain this effect without a thermal mechanism. Usual concepts of plastic flow suggest that the Hugoniot stress state should reside on the yield surface. The data show only a small residual state of shear stress relative to the strength at Hugoniot states greater than about 5 GPa. A transition from normal elastic-plastic response to the observed anomalous behavior appears to occur at about this stress level. A reduced state of shear stress on the Hugoniot and enhanced strength would be expected if the flow stress were small and if some rapid strength recovery mechanism were operating during the microsecond or less before the strength is tested with a release or reloading wave. Heterogeneous deformation and thermal trapping during the high-rate deformation process would be expected to cause reduced flow stress, and microscale thermal quenching after passage of the shock wave could provide the recovery process. Such an explanation has yet to be verified, although, model calculations indicate local shear temperatures consistent with the interpretation [7].

VI. SHOCK-INDUCED PHASE TRANSFORMATION. Processes of coherent phase transformation occurring under shock-wave compression provide a striking example of phenomena affected by microstructures. Coherent transformation processes include recrystallization and twinning, coherent precipitation, and displacive, martensitic or semi-reconstructive transformations in solids, although all of these have not yet been observed under shock loading. These processes are commonly reversible or exhibit little hysteresis in the transition between states which occur through the motion of a coherent interface. Further, nonhydrostatic stresses markedly influence the conditions of phase coexistence both in the bulk and on the microscale where structural defects provide sites of second-phase nucleation. Paterson [27] has reviewed the theoretical development of nonhydrostatic thermodynamics applicable to coherent transformation prior to 1973, and several authors, including Kamb [28], Fletcher [29], and Robin [30], have noted the difficulty in establishing generalized thermodynamic potentials independent of the specific process. They note that coexistence conditions depend on the coherent interface orientation with respect to crystal axes and interface accommodated stress discontinuities in those components not required for stress equilibrium.

The I-II transformation in the naturally occurring mineral calcite is a coherent displacive transformation which has been investigated extensively under stress-wave loading [31,32]. The transformation initiates and proceeds within the elastic range of the material and, in polycrystalline specimens, is sensitive to both the shear stress state and the microstructure of the body. Phase change through the stress wave involves a transformation shape change as well as volume change, and the process leads to highly nonlinear stress-wave response, including wave splitting and rarefaction shocks. Accurate characterization of the stress wave response requires the inclusion of microstructural parameters to account for local stress heterogeneities which affect the range and shear sensitivity of the coherent transformation.

Perhaps the most significant shock-wave phenomena for which a plausible understanding has emerged within the context of a model of heterogeneous deformation and accompanying adiabatic shear and temperature trapping is the 4-to-6 fold coordination quartz-to-stishovite reconstructive phase transformation which occurs in crystalline SiO_2 [33,34]. Equivalent shock-induced phase transformation effects have been observed in a number of silicate minerals as well as other materials [35], however, the behavior of quartz is representative and has historic interest. This thermally-activated transformation requires minutes to hours to complete under static high pressure but is completed within a few ns under shock compression.

Shock-wave studies also note an anomalous metastable Hugoniot [35,36] response through the quartz-stishovite mixed phase region, which relates a fixed mass fraction of transformed material at a particularly Hugoniot pressure. Shock pressures in excess of 20 GPa over the initiation transformation pressure are necessary for complete transformation to the stishovite phase. In addition to the unusual Hugoniot behavior, release wave studies from shock pressures indicate fluid or fluid-like response at the Hugoniot state [34]. The reverse transformation during shock unloading reveals large hysteresis in the complete shock transformation cycle. Shock recovery experiments uncover complex deformation fabric through optical and TEM microscopy. Traces of stishovite and significant quantities of high-density glass are seen in the recovered samples [37,38].

These and other curious shock effects associated with the phase change in quartz as well as other materials are readily understood within the context of a heterogeneous deformation and accompanying adiabatic shear and thermal trapping effect. Calculations show that temperatures associated with localized adiabatic shearing are adequate to accommodate reconstructive transformation through thermally-activated rate processes within the risetime of the shock wave, and thermal quenching after passage of the shock wave accounts for the mass fraction transformed on the metastable Hugoniot [21,23]. Also, local temperatures and thermal conduction rates are consistent with the persistence of laminar melt domains at the shock state and, therefore, the fluid-like release wave behavior. High-density glass in recovered shocked minerals, as well as minerals recovered from impact meteor craters, have been explained within the context of a thermal heterogeneous shock deformation process [39].

VII. SUMMARY. The present report reviews studies focused on understanding and modeling large-amplitude, nonlinear stress-wave propagation in solids. Recently developed time-resolved measuring techniques are providing constraining data in terms of the structure and evolution of stress and particle velocity profiles. The data indicates that microstructural effects are fundamental to the stress-wave propagation phenomena. Constitutive modeling of the dynamic deformation process, with explicit treatment of both the existing and evolving microstructure, is needed to calculate complex stress-wave propagation. More specifically, only through microstructural considerations will important shock-wave effects involving unique physical, chemical, and metallurgical processes be understood and exploited.

REFERENCES

1. W. Band and G. E. Duvall, Amer. J. Phys. 29, 780 (1961).

2. G. E. Duvall and G. R. Fowles, in *High Pressure Physics and Chemistry*, Volume 2, edited by R. S. Bradley, pp. 209-287, Academic Press (1963).

3. I. C. Skidmore, Appl. Mat. Res. 4, 131 (1965).

4. J. R. Asay and L. C. Chhabildas, in *Shock Waves and High-Strain Rate Phenomena in Metals*, edited by M. A. Meyers and L. E. Murr, pp. 417-432, Plenum Press (1981).

5. D. C. Wallace, Phys. Rev. B. 22, 1487 (1980).

6. G. R. Fowles, J. Geophys. Res. 72, 5729 (1967).

7. D. E. Grady and J. R. Asay, J. Appl. Phys. 53, 7350 (1982).

8. D. E. Grady, J. R. Asay, R. W. Rohde, and J. L. Wise, in *Material Behavior under High Stress and Ultrahigh Loading Rates*, edited by J. Mescall and V. Weiss, Plenum Press, 81-100 (1983).

9. J. R. Asay and J. Lipkin, J. Appl. Phys. 49, 4242 (1978).

10. B. M. Butcher, *Shock Waves and the Mechanical Properties of Solids,* edited by J. J. Burke and V. Weiss, Syracuse University Press, p. 277 (1971).

11. M. M. Carrol and A. C. Holt, J. Appl. Phys. 43, 1626 (1972).

12. D. A. Shockey, D. R. Curran, L. Seaman, J. T. Rosenberg, and C. F. Peterson, Int. J. Rock Mech. Min. Sci. 11, 303 (1974).

13. D. E. Grady and M. E. Kipp, Int. J. Rock Mech. Min. Sci. 17, 147 (1980).

14. L. Seaman, D. R. Curran, and D. A. Shockey, J. Appl. Phys. 47, 4814 (1976).

15. A. L. Stevens, L. Davison, and W. E. Warren, J. Appl. Phys. 43, 4922 (1972).

16. D. E. Grady, J. Appl. Phys. 53, 322 (1982).

17. D. E. Mikkola and R. N. Wright, *Shock Waves in Condensed Matter - 1981 (AIP),* edited by W. J. Nellis, L. Seaman, and R. A. Graham (1981).

18. L. E. Murr, in *Shock Waves and High-Strain-Rate Phenomena in Metals,* edited by M. A. Meyers and L. E. Murr, Plenum Press, p. 607 (1981).

19. J. R. Asay and L. C. Chhabildas, *Shock Waves and High-Strain-Rate Phenomena in Metals,* edited by M. A. Meyers and L. E. Murr, Plenum Press, p. 417 (1981).

20. L. C. Chhabildas, J. L. Wise, and J. R. Asay, *Shock Waves in Condensed Matter - 1981 (AIP),* edited by W. J. Nellis, L. Seaman, and R. A. Graham (1981).

21. D. E. Grady, J. Geophys. Res. 85, 913 (1980).

22. Y. Horie, Phys. Rev. B. 21, 5549 (1980).

23. D. E. Grady, *High Pressure Research: Applications in Geophysics,* edited by M. Manghnani and S. Akimoto, Academic Press, p. 389 (1976).

24. J. W. Swegle and D. E. Grady, in preparation.

25. L. C. Chhabildas and J. R. Asay, in *High Pressure in Research and Industry,* edited by C. M. Backman, T. Johannison, and L. Tegner, pp. 183-189 (1982).

26. L. C. Chhabildas, J. L. Wise, and J. R. Asay, *Shock Waves in Condensed Matter - 1981 (AIP),* edited by W. J. Nellis, L. Seaman, and R. A. Graham, 422-426 (1981).

27. M. S. Paterson, Rev. Geophys. 11, 355 (1973).

28. W. B. Kamb, J. Geophys. Res. 66, 259 (1962).

29. R. C. Fletcher, J. Geophys. Res. 78, 7661 (1973).

30. P. Y. F. Robin, Amer. Mineral 59, 1286 (1974).

31. D. E. Grady, R. E. Hollenbach, and K. W. Schuler, J. Geophys. Res. 83, 2839 (1978).

32. D. E. Grady, J. Geophys. Res. 84, 7549 (1979).

33. T. J. Ahrens and J. T. Rosenberg, in *Shock Metamorphism of Natural Minerals*, edited by B. French and N. Short (1968).

34. D. E. Grady, W. J. Murri, and G. R. Fowles, J. Geophys. Res. 79, 332 (1974).

35. G. E. Duvall and R. A. Graham, Rev. Modern Phys. 49, 523 (1977).

36. R. G. McQueen, S. P. Marsh and J. N. Fritz, J. Geophys. Res. 72, 4999 (1967).

37. P. S. DeCarli and D. J. Milton, Science 147, 144 (1965).

38. D. Stoffler, Fortschr. Mineral 49, 50 (1972).

39. J. Arndt, W. Hummel, and I. Gonzalez-Cabeza, Phys. Chem. Minerals 8 230 (1982).